RECOMMENDED PROCEDURES FOR PREDICTING RANDOM VIBRATION ENVIRONMENTS IN MSFC AEROSPACE VEHICLES

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CONTENTS

1. INTRODUCTION

There are many different methods which have been proposed for use, or are being used at the present time, to predict the random vibration environments of modern aerospace flight vehicles. As a result, one is often faced with a dilemma as to which method to use for a given situation. As a first step in deciding which method or methods are most desirable for MSFC applications, all known vibration prediction methods have been reviewed and critiqued with emphasis upon their advantages and disadvantages. The results of this review and critique are presented in Reference 1. The next step is to make a specific selection of optimum techniques for predicting the response of structures to acoustic, aerodynamic, and mechanical excitation based upon the methods presented in Reference 1. Such a selection is the subject of this report. It also presents a discussion and recommendations regarding those techniques which appear to hold the greatest promise and which should be developed further in the near future.

2. SELECTION CRITERIA

Six criteria were established and utilized in deciding which of the various prediction methods are most suitable for immediate use in predicting vibration levels for vehicles of concern to MSFC. These criteria are:

a. The method must be fully developed to a point where it is ready to use on typical launch vehicle structures with presently available computational facilities and equipment.

b. The method should predict environmental vibration for all critical periods during launch.

c. The method should predict reasonable values for present MSFC vehicles.

d. Realistic consideration should be given to all of those factors which are known to affect vibration response.

e. The cost and time required to use the procedure must be consistent with the requirements of the program under consideration.

f. Statistical information is desirable to allow reliability concepts to be incorporated into the selection of design and test levels.

g. History of past use, if available, must be favorable.

Of the five basic prediction approaches discussed in Reference 1 (classical, multiple input, extrapolation, statistical energy, and model), none of the approaches satisfy all of the above requirements. Therefore, of necessity, the method chosen must be a compromise. Since only extrapolation approaches fulfill selection criteria (a), they will be the only ones considered further in this document.

3. PREDICTION OF VIBRATION ENVIRONMENT

The vibration environment of a launch vehicle is usually most severe, and hence of concern for design considerations during liftoff, transonic flight, and/or maximum dynamic pressure flight. In addition, localized areas on motor frame support structure experience significant levels throughout the period of motor burn. Therefore, any technique, or combinations thereof, must be able to predict the vibration environments for all of these conditions.

There are two general types of extrapolation procedures which have been used in the past to predict the vibration environment induced by the sources described above. The first consists of developing a frequency response function from data measured on one or more vehicles. This function is then used to predict levels on a new vehicle. The second is to scale measured data directly from one vehicle to another using standard scaling relationships. Ideally, a frequency response function based upon a large amount of data from several vehicles, would be preferable. However, in practice, data quality has been a problem. Furthermore, most of the frequency response functions have been developed based on data from only a few or perhaps only one vehicle. The frequency response function has not been defined with as much confidence as would be desired, and the effects of the various scaling parameters have not always been determined in a sound manner. In the sections which follow therefore, consideration will be given to the use of either a frequency response function approach, or a data scaling approach, depending upon particular circumstances.

3.1 ACOUSTICALLY AND AERODYNAMICALLY INDUCED VIBRATION

Several different extrapolation techniques for predicting acoustically and aerodynamically induced vibration were described in Reference 1. Each can be classified as a frequency response function method, or as a scaling technique, as follows:

<u>Frequency Response Function Approach</u>

- Mahaffey and Smith Method
- Brust and Himelblau Method
- Eldred, Roberts, and White Method No. 1
- Eldred, Roberts, and White Method No. 2
- Curtis Method
- Franken Method
- Winter Method No. 1

<u>Scaling Approach</u>

- Condos and Butler Method
- Barrett Method
- Winter Method No. 2

If the vehicle under consideration is significantly different from other vehicles, or if insufficient data are available for scaling from similar vehicles, then the frequency response function approach should be used. However, if sufficient data are available from similar type vehicles, then a scaling approach should be used. The selection of the optimum techniques, according to the above criteria, will be made from the methods listed above.

3.1.1 Scaling from Frequency Response Function

Table 1 presents a summary of pertinent details regarding frequency response function prediction methods. A study of this table, and detailed information presented in Reference 1, indicates that the following procedures should be given further consideration: Brust and Himelblau, Franken, and Winter Method No. 1. To accomplish this, tank skin levels were predicted for zone 5-1 of the Saturn I, Block II vehicle during static firing conditions using these techniques. The calculations, results, and comparison with measured values are given in Appendix A. As can be seen, the Brust and Himelblau, and Franken methods give results which in general, are too low and do not approximate the spectrum very well. However, the Winter method gives a good approximation to the measured spectrum, and envelopes the data very well except for the peak in the spectrum. Therefore, it is concluded that for new vehicles, Winter Method Number 1 should be used for preliminary estimates of the vibration environment. Then as measured data becomes available from similar vehicles, this data should be scaled to the new vehicle using the techniques presented in Section 3.1.2.

Based upon the results of Appendix A, a preliminary estimate of the vibration levels expected on two zones of the Saturn V vehicle has been made using Winter Method No. 1. These levels are given in Appendix B.

3.1.2 Scaling from Existing Data

Condos and Butler (Reference 3), Barrett (Reference 4), and Winter (Reference 1) present methods for extrapolating data from one

Table 1. Summary of Methods for Predicting Vibration from a Frequency Response Function

Method	Excitation Sources	Range of Application	Structure and Mounting Configuration	Statistical Considerations	Source of Data
Mahaffey and Smith	Uses measured or predicted acoustic spectrum	Applies to take-off vibration only	Not considered	Confidence lines are provided	B-58 Aircraft
Brust and Himelblau	Uses measured or predicted acoustic spectrum and/or boundary layer turbulence spectrum	Applies to take-off and high q flight vibration	Not considered	Confidence lines are provided	Mahaffey and Smith data
Eldred, Roberts and White Method No. 1	Uses measured or predicted acoustic spectrum	Applies to take-off vibration only	Not considered	Not given, although data scatter is shown	Snark missile
Eldred, Roberts and White Method No. 2	Uses measured or predicted acoustic spectrum	Applies to lift-off vibration only	Not considered	Not given, although data scatter is shown	Unidentified ballistic missiles
Curtis	Uses free stream dynamic pressure	Applies to high q flight vibration only	Distinguishes between internal and external equipment	88 and 98 percentiles for peak values are given	F-8U, B-59, F-101, and F-106 aircraft

Table 1 (continued)

Method	Excitation Sources	Range of Application	Structure and Mounting Configuration	Statistical Considerations	Source of Data
Franken	Uses measured or predicted acoustic spectrum	Applies to lift-off vibration only.	Considers vehicle diameter and surface weight of skin	Not given, although approximate data scatter range is shown	Jupiter, Titan
Winter Method No. 1	Uses measured or predicted acoustic spectrum and/or boundary layer turbulence spectrum	Applies to lift-off and max q flight vibration	Considers three basic structural types, vehicle diameter, weight of structure and equipment	Maximum envelope of data is provided, but no further statistics are given	Skybolt, Jupiter, Titan, Genie, Minuteman

vehicle to another. All three techniques are similar except that Condos and Butler, and Barrett use statistical analyses of the data whereas Winter uses maximum envelopes. Furthermore, Winter normalizes all data to a common reference acoustic pressure and surface weight density, whereas Condos and Butler, and Barrett group data according to vehicle compartment. Since both statistical envelopes and data normalization are desirable, it is suggested that a combination of these two methods be used as follows:

1. Select a flight vehicle to serve as the data vehicle for the predictions. The principal requirements for a good data vehicle are as follows. First, it should be similar in mission and structural design to the new vehicle for which the predictions are required. Second, it should have been the subject of an extensive vibration survey producing measurements at many different structural locations throughout the vehicle.

2. Review and edit the data vehicle measurements to eliminate those data which are obviously distorted by severe clipping, excessive instrument noise, tape dropout, etc.

3. Separate out all data which appear to be caused by direct mechanical excitation from the rocket motor. For actual launch vibration measurements, such data are easily detected since their levels will remain relatively constant throughout the powered phase of launch. The acoustic and aerodynamic induced vibrations, on the other hand, vary widely as the vehicle passes from lift-off through Mach 1 to maximum dynamic pressure. Proceed using only the acoustic and aerodynamic induced data.

4. Compute power spectra in g^2/cps for each vibration measurement during lift-off, transonic flight, and maximum dynamic pressure flight.

5. Review the spectra (and the time histories from which they were computed) for the presence of periodicities. Periodic components can be detected using the techniques in Reference 5. If such periodicities are present, they are probably

due to onboard equipment with rotating parts or self-excited oscillations. They should be removed from the data or ignored. Caution must be exercised to avoid confusing narrow band random data due to resonant structure response with such periodicities.

6. Predict (or determine from measurements) the power spectra in $(psi)^2/cps$ for the excitation pressures, in the region of each vibration measurement, due to lift-off acoustic noise, transonic shock wave—boundary layer interaction, and/or maximum dynamic pressure boundary layer turbulence. To reduce the number of calculations, power spectra should first be predicted in 1/3 octave or octave band widths, and then converted to narrow band power spectrum levels. Therefore, determine the average vibration and acoustic spectrum level (in g^2/cps and psi^2/cps) in each 1/3 octave or octave band of interest.

7. Calculate the average surface weight density in psf for the structure at each vibration measurement location.

8. Compute a reference power spectrum from each vibration measurement during each launch event of interest, as follows:

$$G_r(f) = G_{vd}(f) \frac{w_d^2}{G_{pd}(f)} \tag{1}$$

where

$G_{vd}(f)$ = measured average power spectrum in 1/3 octave or octave band for vibration of data vehicle in g^2/cps

$G_{pd}(f)$ = measured or predicted average power spectrum in 1/3 octave or octave band for excitation pressure on data vehicle in $(psi)^2/cps$

w_d = average surface weight density for data vehicle structure at vibration measurement location

9. Treating the data from each significant launch event separately, segregate the reference spectra into classifications which correspond to the desired structural zones for which vibration is to be predicted. This segregation may be accomplished by either natural selection or predetermined zoning. Segregation by natural selection is accomplished as follows. Visually inspect the reference spectra for clustering which can be correlated with specific structural features. For example, it may be found that the reference spectra for ring frame measurements are generally similar to one another, but significantly different from the reference spectra for bulkhead measurements. Hence, the reference spectra for ring frames would be treated separately to arrive at vibration predictions which are only applicable to ring frame vibration. Predetermined zoning means that it has been decided in advance that separate predictions will be made for ring frame vibration and bulkhead vibration. Hence, the reference spectra are segregated based upon the measurement locations, independent of how the reference spectra may cluster. Note that after the segregation is completed (by either procedure), the reference spectra for different launch events in each zone should be compared for similarity. If the data cluster over similar limits, the spectra for different launch events in each structural zone should be grouped together and treated as a single set.

10. For each set of spectra representing a structural zone, determine a raw upper prediction limit by selecting a desired percentile level for the distribution of the spectra in narrow contiguous frequency intervals. It is suggested that one-third octave frequency intervals be used, although any relatively narrow frequency intervals would be acceptable. The average values of the reference spectra in each frequency interval should be used to select the desired percentile level. The actual selection of the percentile level should be as follows. If at least 100 reference spectra are available for a given structural zone, select the P percentile level by computing the level which exceeds 100 P% of the spectra values. For example, if 100 reference spectra are available, the 0.975 percentile would be that level which is greater than 97 and less than 3 of the spectra values. If

less than 100 reference spectra are available, compute the desired percentile level by fitting an empirical distribution function to the spectra values. If an empirical distribution function is not known, assume a lognormal distribution applies.

11. With the raw upper prediction limit for each structural zone displayed as a log-log plot of spectral density versus frequency, envelope the raw limits with straight line segments to obtain a smoothed prediction limit for each zone.

12. If the diameter of the data vehicle and the new vehicle vary by more than two to one, then the frequency scale (abscissa) of the smoothed prediction limit for each zone should be shifted, as follows.

$$f_n = f_d \left(\frac{D_d}{D_n} \right)^{1/2} \tag{2}$$

where

f_n = frequency for new scale

f_d = frequency for prediction limit scale

D_n = diameter of new vehicle

D_d = diameter of data vehicle

13. Predict the average power spectrum (in psi^2/cps), in each 1/3 octave or octave band of interest, for the excitation pressures along the new vehicle due to lift-off acoustic noise, transonic wave-boundary layer interaction, and/or maximum dynamic pressure boundary layer turbulence. See the Appendix of Reference 1 for details on how these predictions may be accomplished.

14. Estimate the average surface weight density in psf for the structure in each zone of the new vehicle corresponding to a zone in the data vehicle. If the average surface weight density varies significantly in a given structural zone, use a value appropriate for the lightest structure in the zone.

15. Compute an upper prediction limit for the power spectrum of the vibration in each structural zone of the new vehicle as follows:

$$G_n(f) = G_\ell(f)\,\frac{G_{pn}(f)}{w_n^2} \tag{3}$$

where

$G_\ell(f)$ = upper prediction limit, in a 1/3 octave or octave bandwidth, determined from the reference spectra for a given zone in g^2/cps

$G_{pn}(f)$ = predicted power spectrum, in a 1/3 octave or octave bandwidth, for excitation pressure on the given zone of the new vehicle in psi

w_n = average surface weight density for the structure of the given zone for the new vehicle

If the reference spectra for the vibration during various significant launch events was not found to be similar in step 9 then a different function $G_\ell(f)$ will be needed to predict the vibration for each significant launch event. Otherwise, the same $G_\ell(f)$ function will apply for all launch events.

16. If the power spectrum levels $G_n(f)$ that have now been determined, are based on 1/3 octave or octave band measurements, then a correction factor must be applied to $G_n(f)$ to account for the averaging effect over the bandwidth. According to Reference 9, a $G_n(f)$ based on 1/3 octave band or octave band data should be multiplied by a factor of 3 or 5 respectively, to result in the proper $G_n(f)$ which would result from a narrow band power spectrum prediction.

17. With the vibration predictions for each structural zone of the new vehicle displayed as a log log plot of spectral density versus frequency, envelope the predictions with straight line segments to obtain a smoothed prediction for each zone.

3.2 MECHANICALLY INDUCED VIBRATION

The only method which has bee proposed for scaling mechanically induced vibration is the method proposed by Barrett in Reference 3. Therefore, it is recommended that this method be used in all instances for this type of vibration. Note that this procedure, however, should be applied only to those structural zones where the data do not vary significantly during launch, as determined in step 3 of Section 3.1.2.

4. RECOMMENDATIONS FOR FURTHER DEVELOPMENT

As a result of the present study, it is recommended that further work be performed to improve extrapolation, model, and statistical energy methods. The model and statistical energy methods are recommended because, in time, they appear to hold the greatest promise for replacing or complementing extrapolation methods. The extrapolation method, although currently the most workable, needs significantly more development to interpret properly data that are used in preparing a frequency response function, and to define adequately the effects of such parameters as vehicle diameter, equipment weight, boundary layer noise efficiency, transonic excitation efficiency acoustic noise efficiency, etc.

Specific recommendations for further development of these methods are given in the paragraphs which follow. Additionally it is recommended that, at the present time, further development work be limited on classical and multiple input methods because of their inherent difficulties and mathematical intractability for all but the most simplified and idealized structures.

4.1 EXTRAPOLATION APPROACH

A significant improvement in extrapolation approaches will be realized by accomplishing three separate tasks. The first task is concerned with determining, with greater accuracy, the relative efficiencies of acoustic noise, transonic excitation, and aerodynamic noise, in inducing vibration in a structure. The second task is concerned with defining empirically, in greater detail, the frequency response function, and the effect of structural parameters upon the resulting vibration. The third task is concerned with improving methods for predicting mechanically induced vibration. A discussion of these tasks is given below.

4.1.1 Determining Relative Efficiencies of Acoustic Noise, Transonic Buffet, and Aerodynamic Noise

A previous analytical study has been performed relating the relative efficiency of acoustic and boundary layer noise (Reference 6) in inducing vibration in structures. In addition, limited studies (References 7 and 8) on a small quantity of data have determined this relationship empirically. Unfortunately, the results have shown a great deal of scatter and, of course, do not include data which is now available.

The vibration environment caused by fluctuating pressures encountered during transonic flight has received even less attention. For one thing, no notable attempt has been made to determine analytically "equivalent acoustic fields" for transonic shock wave—boundary layer interaction. Also, no empirical studies have been undertaken.

In light of the above discussion, the following tasks are suggested to determine the actual efficiencies of acoustic noise, transonic excitation, and boundary layer noise.

Task 1 Perform a study to determine, analytically, the relative efficiency of acoustic noise and transonic excitation in inducing random response in typical flight vehicle structure.

Task 2 Utilizing the analytical relationships determined from Reference 6, and Task 1 above, perform statistical analyses on all applicable available flight data to determine the most realistic efficiency conversion factors relating acoustic noise, transonic excitation, and aerodynamic noise in their ability to induce vibration in a structure. Take into consideration the possible effects of nonlinearities. Part of this task will be to investigate all data prior to use to ensure that proper reduction techniques have been utilized (stationary versus nonstationary, sine versus random, etc.) and to ensure that corrections are made to the data to account for finite transducer size.

4.1.2 Determination of Frequency Response Function and Effect of Structural Parameters

Many of the problems that have arisen in the past in developing and using frequency response functions stem from the fact that the raw data were improperly analyzed and improperly normalized in developing the frequency response function. Some of the inadvertent errors or oversights that have been made in the past include the following:

1. Nonstationary data have been analyzed as stationary data.
2. Sinusoidal data have been analyzed as random data.
3. Data which have exceeded band-edge and, hence, have been "clipped" during acquisition have been used without corrections.
4. Corrections have not been applied to the data to account for the effect of the data acquisition system noise floor.
5. Corrections have not been applied to the data to account for the frequency response characteristics of the data acquisition and reduction systems.
6. The effect of accelerometer mounting block resonances has not been considered in analyzing the data.

7. Measurements made on skin, equipment mounting points, and internal equipment items have been grouped together indiscriminately.

8. The structural weight parameters which affect response have not been properly considered. For example, the weight of the external skin panel alone is not sufficient, since internal airframes, plumbing, and other equipment items will all affect the response. The question is, how much do these individual items affect the response, and to what extent?

As a result of the errors and problems listed above, it is recommended that a new frequency response function be derived from data taken on several types of vehicles, taking care to consider all the factors itemized above. If these factors are not considered, no real progress can be expected to be made in improving the usefulness of frequency response functions. As a result, the following program is recommended.

1. Assemble data from several representative vehicles.
2. Obtain a detailed description of all parameters suspected of affecting vibration response.
3. Remove all sinusoids and questionable data.
4. Apply correction factors to data, where necessary, to account for frequency response characteristics of data acquisition and reduction systems.
5. Remove from the data all samples which appear to be caused by direct transmission through the vehicle structure from the rocket motor.
6. Perform statistical analyses on the data, taking into consideration those parameters believed to affect significantly the vibration response.
7. Based on the results of item 6, determine the best form of the frequency response function and the effect of scaling parameters. Determine confidence limits for the frequency response function.

4.1.3 Improving Techniques for Predicting Mechanically Induced Vibration

The only extrapolation method available for predicting mechanically induced vibration levels is the one developed by Barrett (Reference 3). This method and its derivation appear reasonable for use on vehicles similar to Saturn I if properly interpreted. However, before it can be applied with any degree of confidence to significantly different vehicles, the following points should be considered.

1. In the development of the prediction technique, it is assumed that the ratio of vibration power to potential mechanical power is the same for both the reference vehicle and the new vehicle. The mechanical power is expressed as the product of rocket engine thrust and rocket engine exhaust gas velocity. It is reasonable to suspect that this ratio is not constant, and will vary, for example, with differences in mechanical impedance between the motor and the thrust structure.

2. An attenuation factor which takes into account the effect of component mass loading on the new structure is given as

$$F = \frac{W_n}{W_n + W_c}$$

where

W_n = total weight of new beam structure

W_c = weight of a component mounted in this area

This attenuation factor does not seem reasonable since even a very heavy component would not appreciably affect the ratio of $(W_n)/(W_n + W_c)$. It appears that the weight of the local structure surrounding the component should be used instead of the quantity W_n. Further modification to the attenuation factor is also necessary if components are mounted near data pickups on the reference vehicle.

Thus the equation for the prediction of mechanically induced vibration can be rewritten as follows:

$$G_n(f) = G_r(f) \left(\frac{W_r}{W_n} \right) \left(\frac{T_n V_n}{T_r V_r} \right) \left(\frac{w_n}{w_n + w_{cn}} \right) \left(\frac{w_r + w_{cr}}{w_r} \right) \qquad (4)$$

where

$G_n(f)$ = predicted power spectrum for the vibration of a specified local area of the mechanically excited structure of a new vehicle, in g^2/cps.

$G_r(f)$ = power spectrum for the vibration measured on a specified local area of the mechanically excited structure of the reference vehicle, in g^2/cps.

W_r = weight of the entire reference structure

W_n = weight of the entire new structure

w_n = weight of a local section of structure on the new vehicle

w_{cn} = weight of components on the local section of new vehicle structure

w_r = weight of a local section of structure on the reference vehicle

w_{cr} = weight of components on the local section of reference vehicle structure

In light of the above two points, the following program is proposed:

1. Acquire mechanically induced vibration data from a wide range of vehicles. Also assemble other vehicle parameters such as thrust, weight, structural descriptions, etc., as required below.

2. Determine the ratio of the vibration power to potential mechanical power for liquid and solid motors for various structural types and motor mounting configurations.

3. Look at both loaded and unloaded mechanically excited structure to evaluate the effect of component mass loading for various types of structure.

4. Using multiple regression analyses, determine an optimum prediction technique for mechanically induced vibration.

4.2 MODEL APPROACH

Due to the distributed nature of structures and environmental excitations, the simulation procedures for ordinary differential equations are not applicable. What is required is a modeling procedure for partial differential equations wherein the procedure is:

1. suitable for gross vehicle behavior as well as the vibratory response of local structure

2. amenable to random loading as well as arbitrary deterministic functions of space and time

3. convenient for parametric variations in either the structural configuration and/or the input excitation

4. convenient for modification to include test data from experimental studies and/or flight test programs.

One such approach, allowing for the above requirements, employs electrical analog and energy concepts to develop a basic model which is equivalent to a discretized physical model, or a form of finite differences mathematical model. By initially using this "circuitous" approach, the resultant electrical model can accommodate nonuniform geometries and physical properties, and is topologically similar to a discretized mechanical model. Thus, if desired, the equivalent mechanical counterpart can be selected for study in lieu of an analog circuit. Such models are available for structural components as Bernoulli-Zulev beams, Timoshenko beams, curved beams, flat plates of both rectangular and circular geometry, shear panels of arbitrary geometry, and cylindrical shells.

By being aware of this circuitous approach, methods of circuit analysis and synthesis now can be employed directly to examine structural problems in addition to those more well-known techniques associated with discrete system dynamics and finite difference analyses. Conversely, existing large scale digital computer programs can be used to analyze such models rather than only on analog circuits per se.

To further implement this modeling approach in order to more closely simulate realistic physical systems (this is in contrast to idealized analytical models), several tasks should be considered:

1. develop methods for routinely modifying the existing basic models incorporating changes dictated by experimental results such as impedance measurements. It is believed that model simplification will result
2. examine methods for including nonlinearities
3. examine attenuation characteristics of existing structural design with a view toward design modification to minimize response at any arbitrary position (say an attachment location for guidance equipment)
4. examine circuit analysis techniques with a view toward structural dynamics applications
5. examine methods for extending resolution of analog models at higher frequencies. This task would include methods for approximating the higher frequency effects on rms and peak responses
6. examine methods for efficiently simulating random input excitations with arbitrary spatial correlation functions

7. examine methods for converting an analog model to a modal simulation. Other than engineering interest, this task could prove useful in support of other digital computer analyses. For example, the effect of a local structural change for (1) the model characteristics of the vehicle and or (2) the local dynamic characteristics at another location can be assessed.

4.3 STATISTICAL ENERGY APPROACH

The statistical energy approach to vibration and acoustic prediction, when used properly, can be an extremely powerful tool. When improperly applied to the wrong type of problem it is just as useless as any misapplied technique. Because of its relative newness and novelty of approach it has not been accepted with confidence by designers. By continued research, the conditions of applicability and required assumptions can be made more definite and improved confidence can be placed in the results.

While there is a need to expand the general theory, the most pressing need is for documented proof of the validity of the assumptions. This must come by a combined program of theoretical and experimental research. Specifically, the concept of energy flow in multi-element systems must be investigated. Only when this is thoroughly examined, and means are developed for generating the coupling factors in a satisfactory manner can the method be considered as truly workable. Research must be directed toward these coupling factors and ways to determine them, both analytically and experimentally.

Because the main advantage of the statistical energy approach lies in averaging over a frequency band or over many vibrating modes, it is imperative to know how sensitive the result is to the averaging procedure. Confidence bounds on the predictions as a function of the bandwidth, modal density and other factors must be developed. They must be developed analytically and checked with well designed physical experiments. This type of analysis is very necessary, for if the variance of the prediction is very high, the confidence in the result is low and the net result may be no better than a prediction based upon extrapolation or other methods. This naturally leads to a study which will determine the optimum method of analysis to be used in any circumstance.

In summary, the needed research can be broken down into several explicit tasks. These are listed below:

1. Development of general theory for multi-element systems
2. Check validity of assumptions from physical point of view
3. Determine sensitivity of analysis to assumptions
4. Develop theoretical and experimental techniques for coupling factor determination
5. Develop confidence estimates for predictions

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APPENDIX A

COMPARISON OF FREQUENCY RESPONSE FUNCTION METHODS WITH MEASURED DATA

To compare results using several prediction procedures with static firing data, a zone from the Saturn I, Block II vehicle was selected. The unloaded tank skin structure of zone 5-1 was chosen because it offered the only readily usable data available from Saturn I. Although several accelerometers were located on tanks during testing, most of these measured low vibration levels apparently due to the liquid within the structure. However measurement location 84.0027-4 (tank F-4, station 859) just aft of the forward full bulkhead appeared to be above the liquid surface during data acquisition. Available data from this location consisted of nine plots of g_{rms} versus frequency from vehicles SA-8, 9, and 10. To convert these data to the more usable power spectrum form, points were selected at 50 cps intervals from 0-2000 cps. Then the g_{rms} value for each point was squared and divided by the filter bandwidth to produce a g^2/cps value for each point. These data points are shown in Figure A-1. Also shown on the figure are a few selected 95th percentile points determined from the data.

The prediction of vibration levels for zone 5-1 required sound pressure levels during static firing and the tank skin surface weight density, which are given in Figure A-2. The derivation of predicted levels using the Winter, Franken, and Brust and Himelblau procedures is described in the following paragraphs. The results are plotted on the data of Figure A-1.

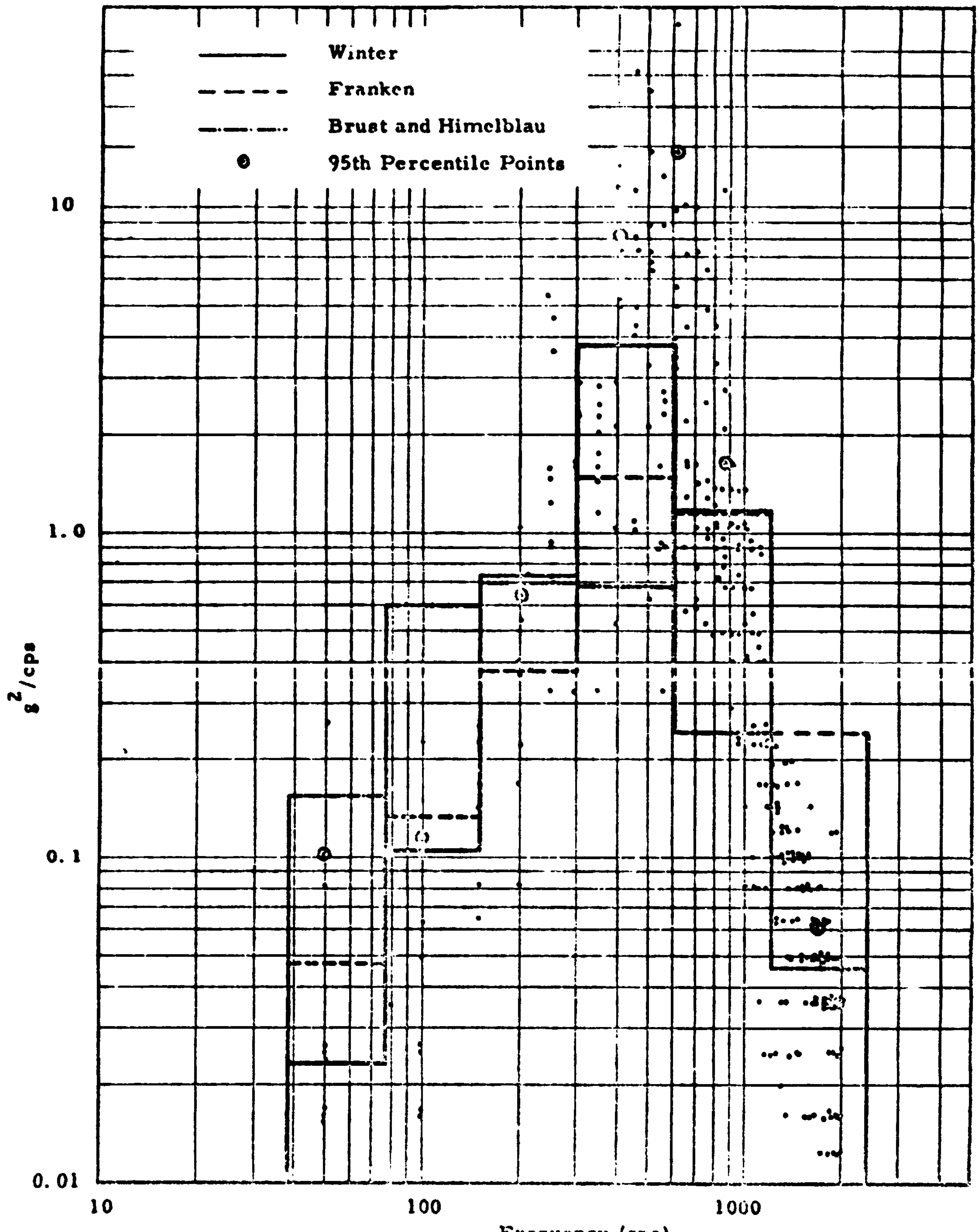


Figure A-1. Comparison of Predicted and Measured Vibration Levels for Tank F-4 Saturn I

Octave Band	Geometric Mean Frequency	Static Firing Octave Band Acoustic Levels
37.5-75	53	139.8
75-150	106	143.8
150-300	212	146.8
300-600	425	148.3
600-1200	850	142.8
1200-2400	1700	139.8

Tank skin thickness = 0.090 per 30M00045

$W = (0.1)(144)(0.090) = 1.3 \text{ lb/ft}^2$

Figure A-2. Saturn I, Block II, Zone 5-1 Octave Band Sound Pressure Levels and Skin Weight Density

The numerical details of the Winter procedure are shown in Figure A-3. The values given in Column 6 were picked from the Winter frequency response function curve of Figure A-4. These values, when combined with the quantities in Column 5 (sound pressure minus $20 \log_{10} W$), yield a vibration level in dB for each octave band. In Column 8, each value has been converted to a quantity in g's using the following relation:

$$20 \log_{10} g_i = dB_i \qquad i = 1, 2, \ldots, 6$$

where

g_i = value of g in ith octave band

dB_i = value in Column 7 for ith octave band

Column 9 is obtained as follows.

$$(g^2/cps)_i = \frac{(g_i)^2}{B_i}$$

where

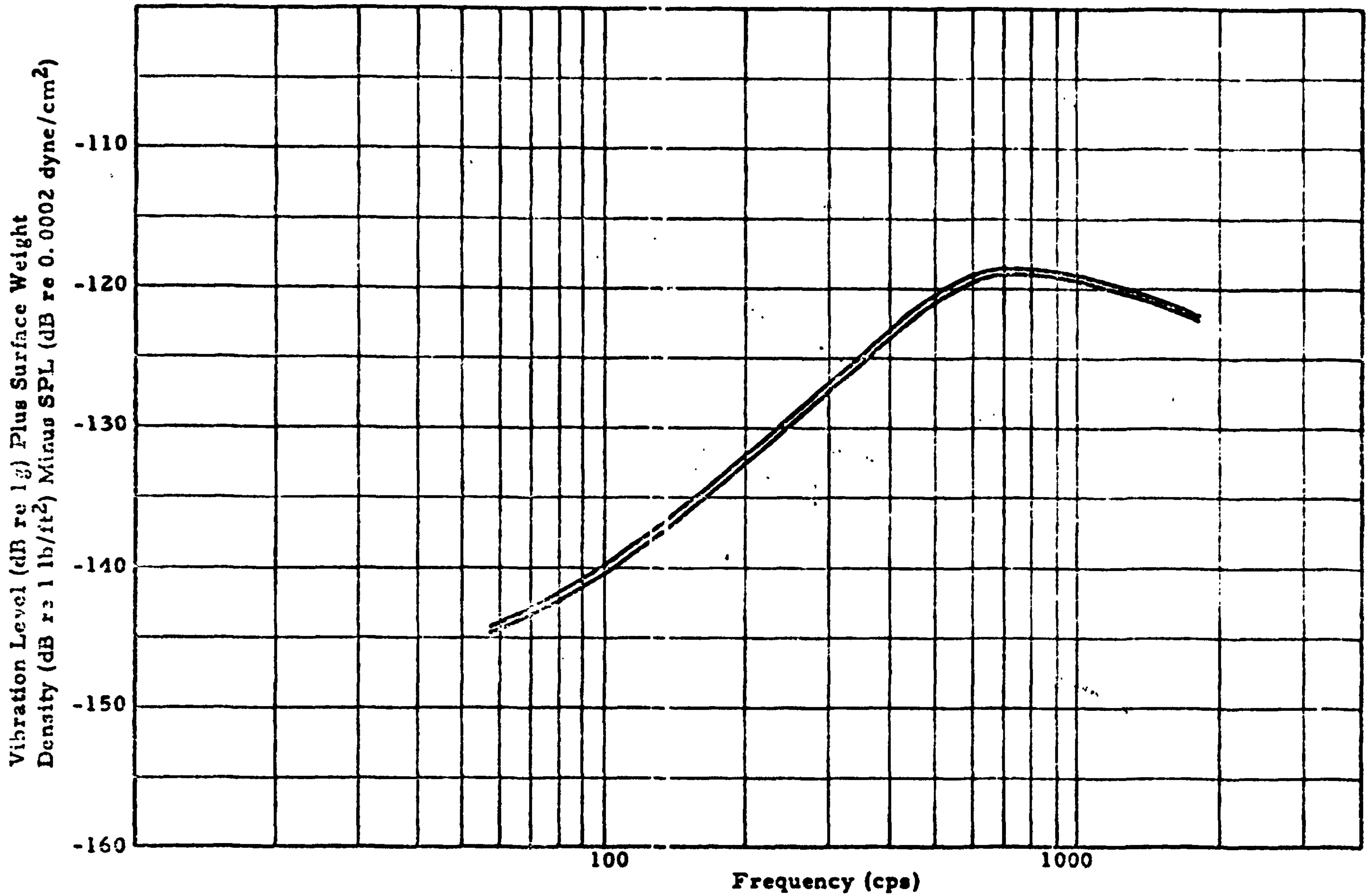
B_i = bandwidth of the ith octave band

The final step consists of multiplying the g^2/cps values in Column 9 by five to convert the wideband levels to narrowband levels to account for the averaging effect of the filters (Reference 9).

The Franken procedure (Figure A-5) is similar to that of Winter but differs in the method used to select the transfer function values of

1	2	3	4	5	6	7	8	9	10
Octave Band	Geometric Mean Frequency	Static Firing Octave Band Acoustic Levels	$20 \log_{10} W$	Sound Pressure Minus $20 \log_{10} W$ Col. 3-Col. 4	Value Picked from FRF	Vibr. Level in dB Col. 5+ Col. 6	g's	g^2/cps	Narrow Band Vibr. Col. 9 times 5
37.5-75	53	139.8	2.3	137.5	-145	-7.5	.422	.0047	.0235
75-150	106	143.8	2.3	141.5	-139.5	2.0	1.26	.021	.105
150-300	212	146.8	2.3	144.5	-131	13.5	4.73	.149	.745
300-600	425	148.3	2.3	146.0	-122.5	23.5	14.96	.746	3.73
600-1200	850	142.8	2.3	140.5	-119	21.5	11.9	.236	1.18
1200-2400	1700	139.8	2.3	137.5	-122	15.5	5.96	.030	.15

Figure A-3. Prediction of Vibration Levels for Saturn I Tank Skin, Zone 5-1, Using Winter's Frequency Response Function


-110
-120
-130
-140
-150
-160
100
1000
Frequency (cps)
Vibration Level (dB re 1g) Plus Surface Weight
Density (dB re 1 lb/ft^2) Minus SPL (dB re 0.0002 dyne/cm^2)

1	2	3	4	5	6	7	8	9	10
Octave Band	Geometric Mean Frequency	Static Firing Octave Band Acoustic Levels	$20\log_{10} W$	Sound Pressure Minus $20\log_{10} W$ Col. 3-Col. 4	Value Picked from TF	Vibr. Level in dB Col. 5+ Col. 6	g's	g^2/cps	Narrow Band Vibr. Col. 9 times 5
37.5-75	53	139.8	2.3	137.5	-142	-4.5	.596	.0095	.047
75-150	106	143.8	2.3	141.5	-138.5	3.0	1.41	.027	.133
150-300	212	146.8	2.3	144.5	-134	10.5	3.35	.075	.374
300-600	425	148.3	2.3	146.0	-126.5	19.5	9.44	.297	1.485
600-1200	850	142.8	2.3	140.5	-119	21.5	11.88	.235	1.176
1200-2400	1700	139.8	2.3	137.5	-120	17.5	7.5	.047	.234

Figure A-5. Prediction of Vibration Levels for Saturn I Tank Skin, Zone 5-1, Using Franken's Transfer Function Curve

Column 6. The Franken transfer function curve (Figure A-6) has an abscissa in frequency times vehicle diameter (cps-ft). To convert to a frequency scale, the abscissa is divided by the tank diameter (70 inches $\simeq$ 6 feet). Then a value may be selected from the curve for each octave band geometric mean frequency. The wide band predicted levels in g^2/cps are multiplied by five to convert to the narrow band levels shown in Column 10.

The Brust and Himelblau procedure does not actually apply to the prediction of skin levels. To alleviate this problem, 95th percentile curves were drawn as shown in Figures A-7 and A-8 and used in place of the 60th percentile curves. The predicted wideband results are shown in Column 4 of Figure A-9. The narrow band predicted levels (wide band times 5) are shown in Column 5.

A final predicted spectrum level for Saturn I has been determined from the Winter Method by enveloping the octave band levels as shown in Figure A-10. As can be seen, this predicted level envelopes the data very well except that it underpredicts the peak of the spectrum by a factor of approximately 4.

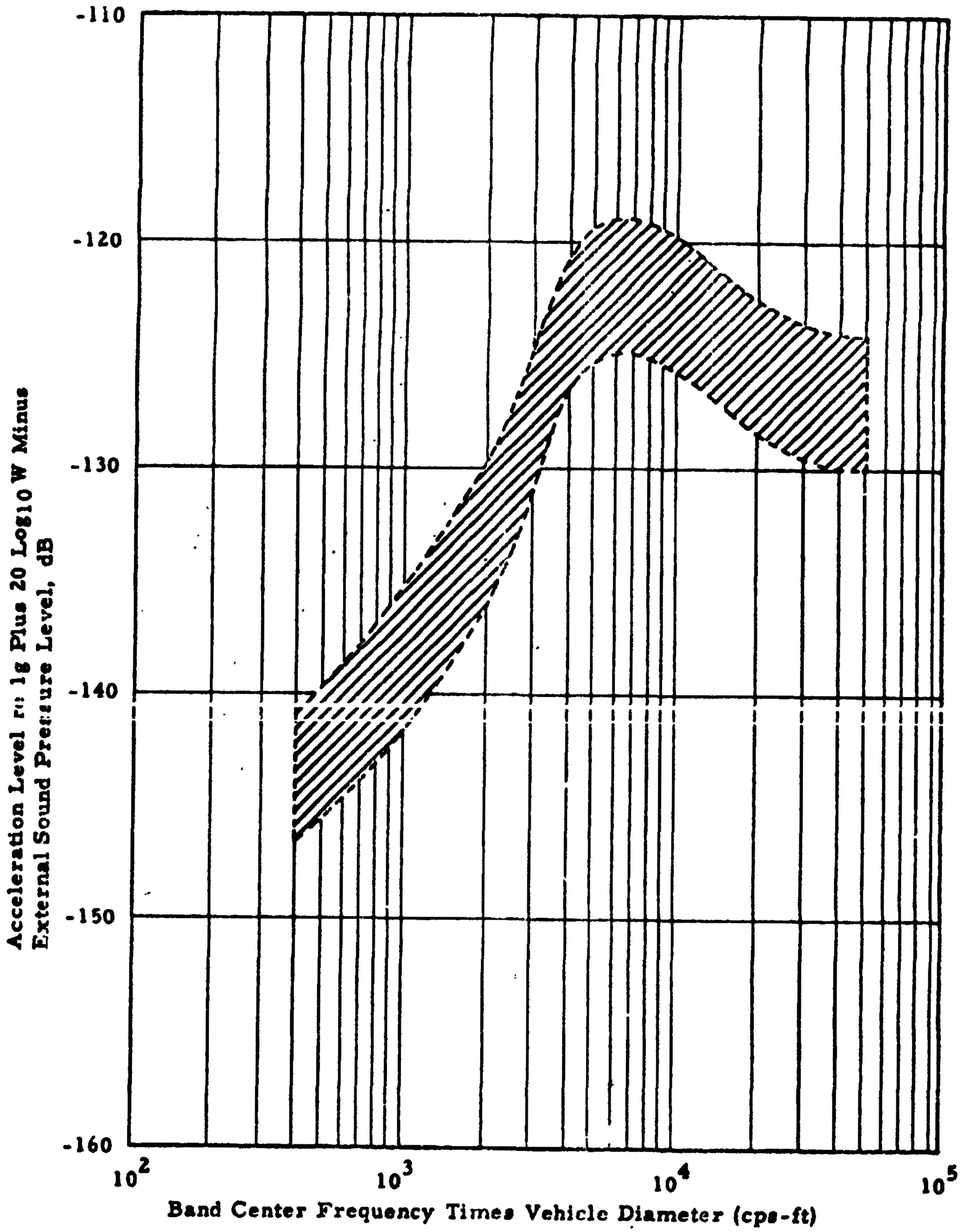


Figure A-6. Franken Transfer Function

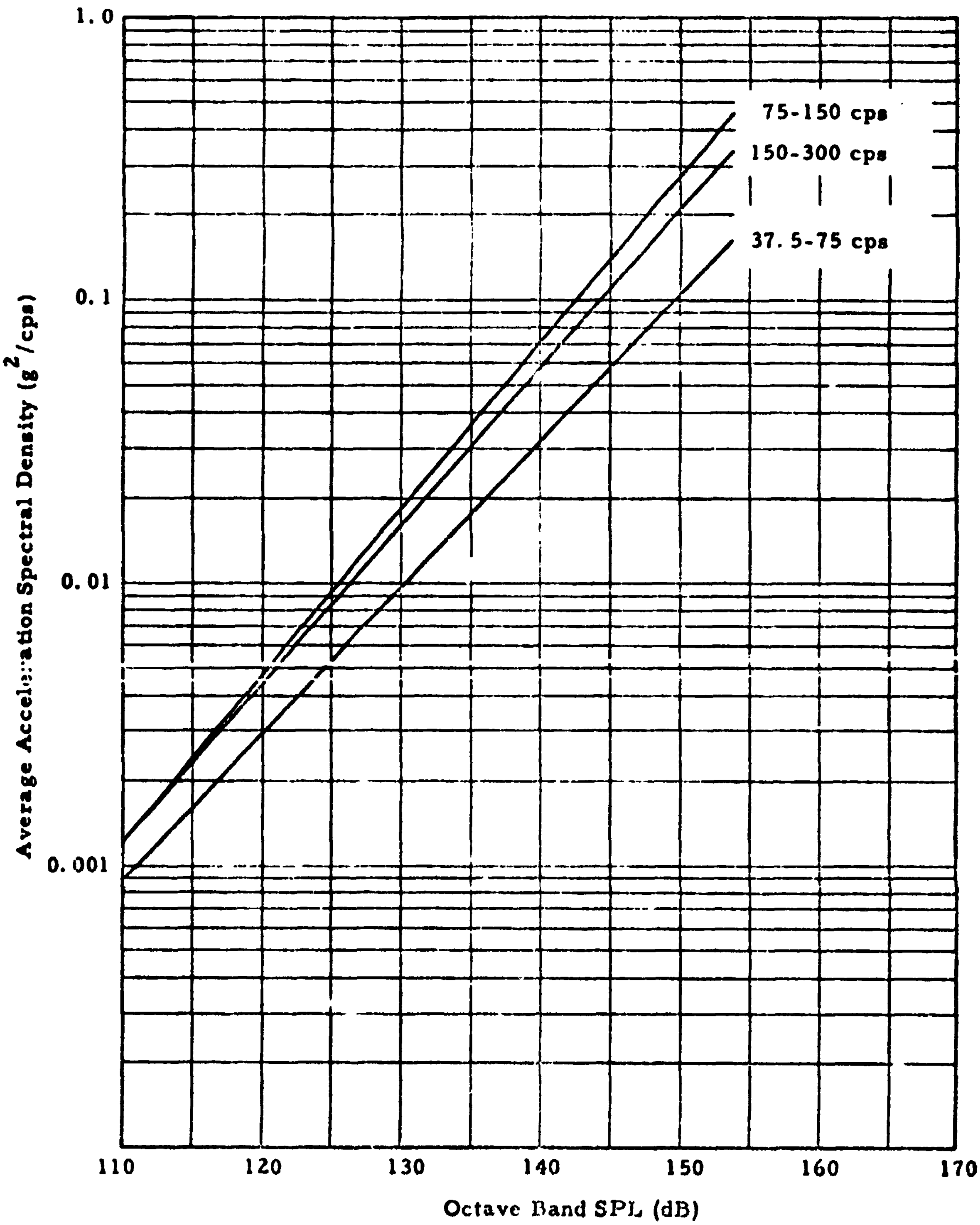


Figure A-7. Brust and Himelblau 95th Percentile Curves

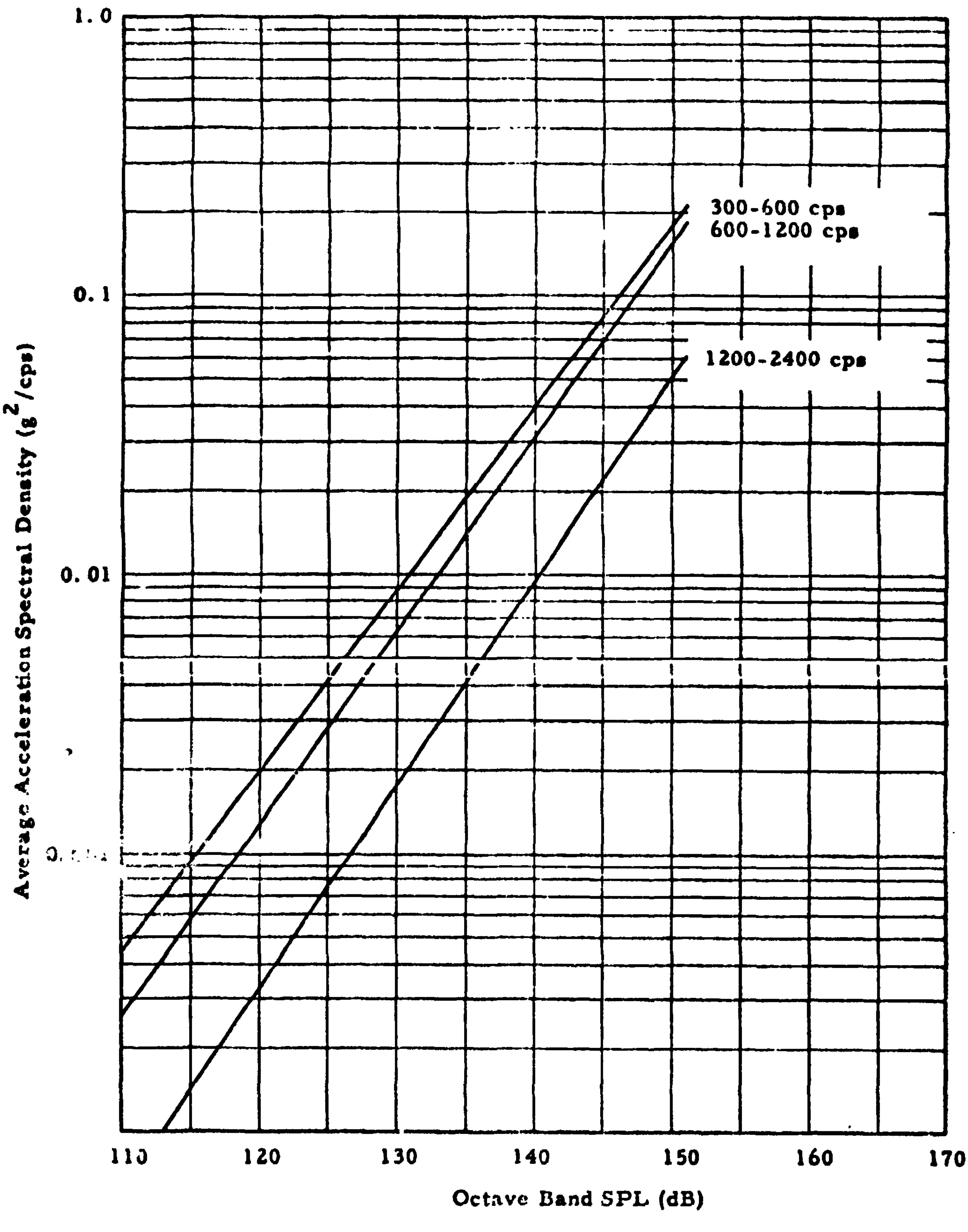


Figure A-8. Brust and Himelblau 95th Percentile Curves

1	2	3	4	5
Octave Band	Geometric Mean Frequency	Static Firing Octave Band Acoustic Levels	Vibration Levels (g^2/cps) Wideband	Vibration Levels (g^2/cps) Narrowband
37.5-75	53	139.8	.031	.155
75-150	106	143.8	.12	.6
150-300	212	146.8	.14	.7
300-600	425	148.3	.135	.675
600-1200	850	142.8	.049	.245
1200-2400	1700	139.8	.0093	.0465

Figure A-9. Prediction of Vibration Levels for Saturn I Tank Skin, Zone 5-1, Using Brust and Himelblau 95th Percentile Curves

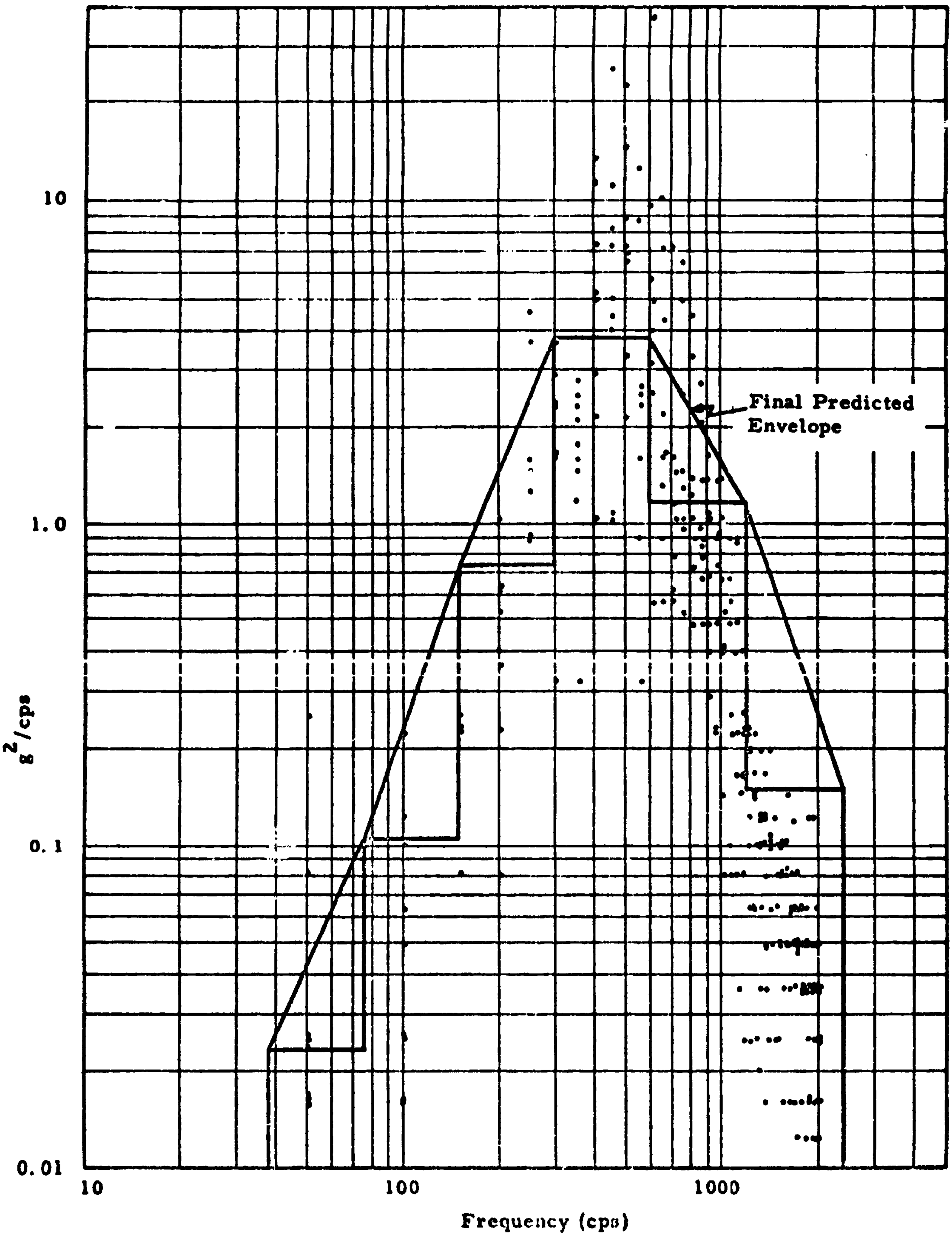


Figure A-10. Predicted Levels for Tank F-4 Saturn I

APPENDIX B

SAMPLE PREDICTION OF VIBRATION LEVELS FOR SATURN V

This section presents predicted vibration levels for two selected zones on the Saturn V vehicle. These zones are the center skirt skin zone 5-2-2 and the forward skirt skin zone 7-2-2. The final results using the Winter procedure are shown in Figures B-1 and B-2.

The prediction calculations are similar to those presented in Appendix A, and are shown in Figures B-3 and B-4. The acoustic levels in Column 3 were obtained by converting static firing data to octave band data. The frequency response function values shown in Column 6 were obtained from Figure A-4 by shifting the frequency scale according to the following relationship:

$$f_n = \left(\frac{D_d}{D_n} \right)^{1/2} f_d = \left(\frac{10}{33} \right)^{1/2} f_d = 0.55\, f_d$$

where

f_n = frequency of new vehicle

f_d = frequency of old vehicle

D_d = diameter of data vehicle (for Winter's FRF, D_d = 10 feet)

D_n = diameter of new vehicle

Thus each frequency for the Saturn V vehicle is 0.55 times the data vehicle frequency. The frequency response function with the shifted frequency scale is shown in Figure B-5.

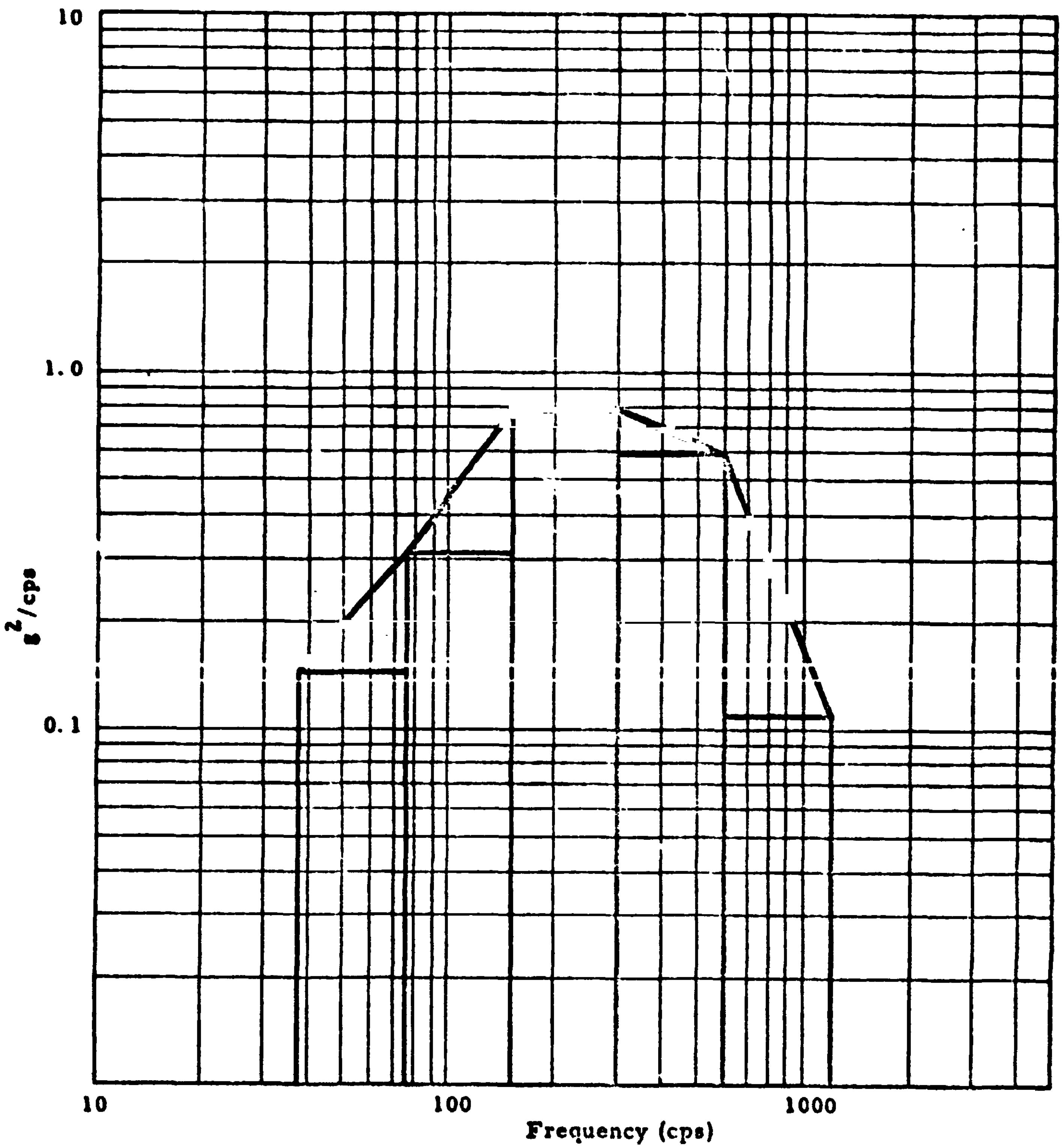


Figure B-1. Predicted Levels for Zone 5-2-2 Center Skirt Skin

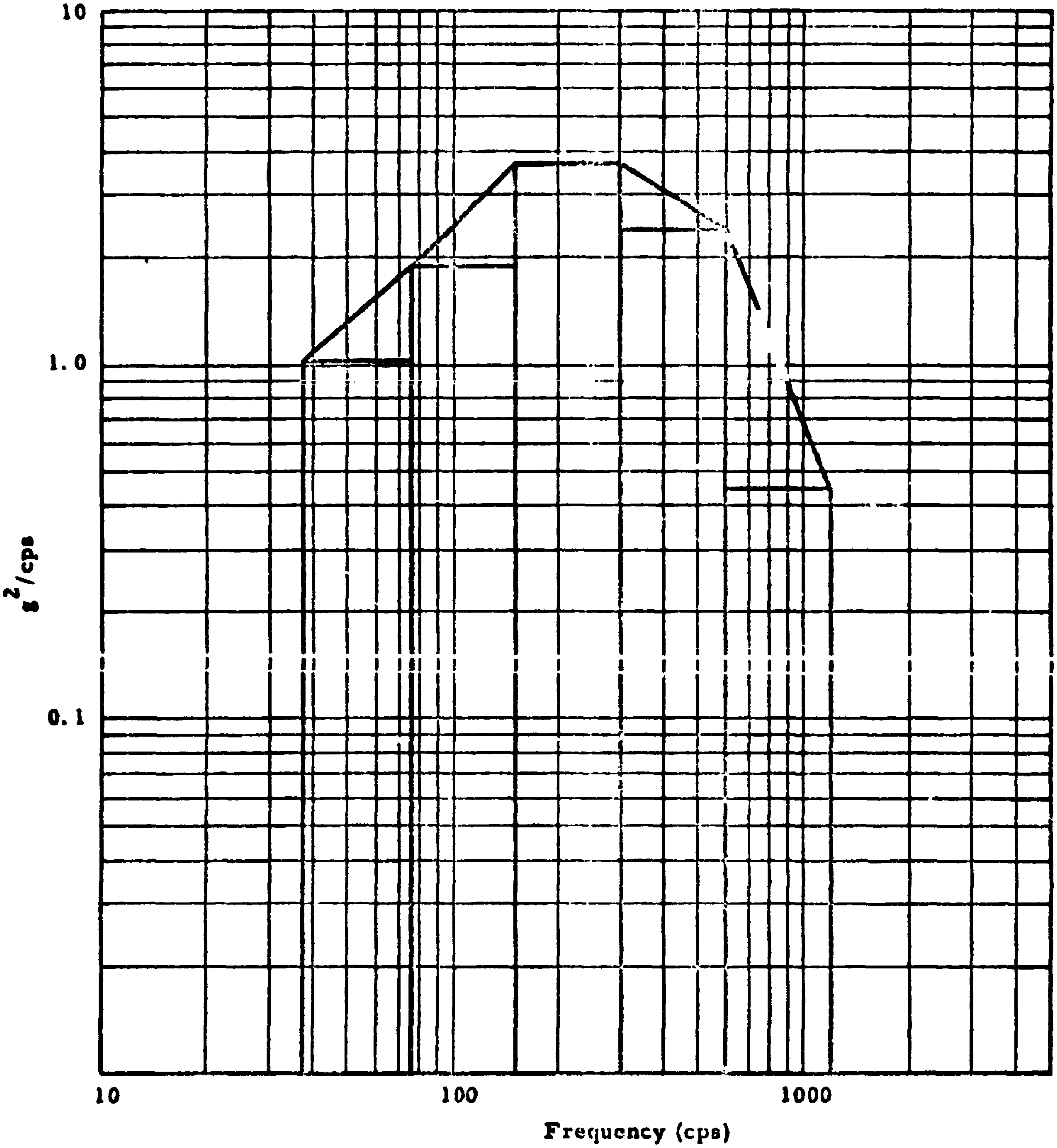


Figure B-2. Predicted Levels for Zone 7-2-2 Forward Skirt Skin

1	2	3	4	5	6	7	8	9	10
Octave Band	Geometric Mean Frequency	Static Firing Octave Band Acoustic Levels	$20\log_{10} W$[1]	Sound Pressure Minus $20\log_{10} W$ Col. 3-Col. 4	Value Picked from FRF[2]	Vibr. Level in dB Col. 5+ Col. 6	g's	g^2/cps Wideband	g^2/cps Narrowband Col. 9x5
37.5-75	53	148.8	8.5	140.3	-140	.3	1.04	.029	.145
75-150	106	147.3	8.5	138.8	-132	6.8	2.19	.064	.32
150-300	212	145.3	8.5	136.8	-123	13.8	4.9	.16	.80
300-600	425	142.3	8.5	133.8	-119	14.8	5.5	.10	.50
600-1200	850	140.8	8.5	132.3	-121	11.3	3.67	.022	.11
1200-2400	1700	142.8	8.5	134.3					

[1] Using a skin thickness of 0.185 inch
$W = 2.664$ lb/ft^2

[2] Horizontal frequency scale shifted so that $f_n = \left(\frac{10}{33}\right)^{1/2} f_d = 0.55 f_d$

Figure B-3. Predicted Vibration Levels for Saturn V, Center Skirt Skin, Zone 5-2-2, Using the Winter Transfer Function Curve

1	2	3	4	5	6	7	8	9	10
Octave Band	Geometric Mean Frequency	Static Firing Octave Band Acoustic Levels	$20\log_{10}W$[1]	Sound Pressure Minus $20\log_{10}W$ Col. 3 - Col. 4	Value Picked from FRF[2]	Vibr. Level in dB Col. 5+ Col. 6	g's	g^2/cps Wideband	g^2/cps Narrowband Col. 9x5
37.5-75	53	152.3	3.2	149.1	-140	9.1	2.85	.217	1.085
75-150	106	149.8	3.2	146.6	-132	14.6	5.37	.38	1.9
150-300	212	146.8	3.2	143.6	-123	20.6	10.7	.76	3.8
300-600	425	143.9	3.2	140.6	-119	21.6	12.0	.48	2.4
600-1200	850	141.8	3.2	138.6	-121	17.6	7.59	.096	.48
1200-2400	1700	141.3	3.2	138.1					

[1] Using a skin thickness of 0.100 inch
$W = 1.44\ lb/ft^2$

[2] Horizontal frequency scale shifted so that $f_n = \left(\frac{10}{33}\right)^{1/2} f_d = 0.55\ f_d$

Figure B-4. Predicted Vibration Levels for Saturn V, Forward Skirt Skin, Zone 7-2-2, Using the Winter Transfer Function Curve

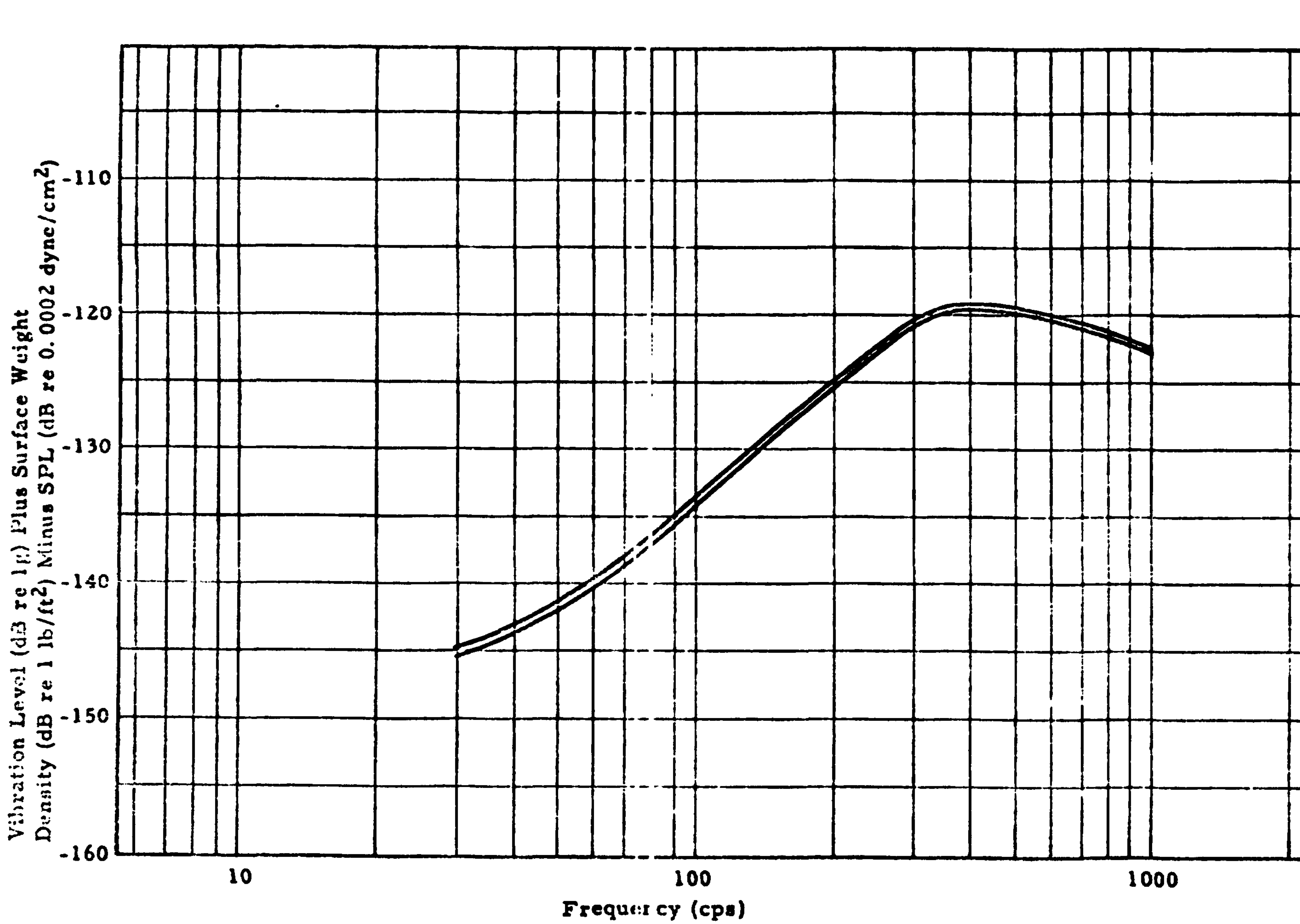


Figure B-5. Winter FRF with Shifted Frequency Scale for Saturn V Vehicle